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Which policy is more effective, carbon reduction in all industries or in high energy-consuming Industries?——From dual perspectives of welfare effects and economic effects

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ABSTRACT

Carbon emission reduction policy is the main method to curb carbon emissions and tackle climate change. However, few studies have investigated the effectiveness of carbon emission reduction polices from the welfare and economic perspectives. This study establishes a dynamic general equilibrium model with input-output structure, and compares the effects of emission reduction in all industries and in high energy-consuming industries. The main conclusions are that carbon emission reduction constraints for all industries have more significant negative impacts on consumption and social welfare compared to emission reduction constraints for high energy-consuming industries. To be more precisely, carbon emission reduction in high energy-consuming industries has comparative advantages in maintaining social welfare stability. Regarding economic effects, compared with the carbon emission reduction in high energy-consuming industries, carbon emission reduction in all industries leads to a larger decline in total output and outputs of most industries. However, the role of carbon emission reduction in all industries is more significant in promoting employment. The carbon emission reduction policies of all industries and high energy-consuming industries have strengths in economic effects respectively. The findings could provide references for the government to take appropriate measures to promote carbon emission reduction and economic growth.

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1. Introduction

The fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) pointed out that more than half of the increase in global average surface temperature observed from 1951 to 2010 was most likely due to the man-made increase in greenhouse gas concentrations. Economic production activities and related energy consumption are the main causes of carbon emissions. Therefore, controlling carbon emissions inevitably has influences on economic development, raising the concern that carbon emission reduction may impede domestic economic development and employment growth. Under the influence of the United States' declaration of withdrawal from the Paris Agreement, the uncertainty in addressing climate change and carbon emission reduction has increased worldwide. In 2017, due to the increase in energy demand, global energy-related carbon dioxide (CO_2) emissions increased by 460 million tons, and were up 1.4% year-on-year. Three consecutive years of carbon emissions' stagnation had ended, which is replaced by a strong rebound. It means that the efforts in the global to address climate change are still obviously insufficient and the situation to prohibit carbon emissions from rising is still very severe.

Currently, China is the largest carbon emission country from all over the world, and an active international participant in carbon emission reduction. In the national independent target submitted to the United Nations, China points out that by 2030, the CO_2 emission per unit of GDP, that is, carbon intensity will decrease by 60%–65% compared to 2005. The carbon emission reduction target has exerted a certain pressure on economic growth and structural transformation of China. In particular, as the largest developing country in the world, China has a large number of poor people, and it is urgent for China to promote economic growth and social welfare. Therefore, China faces a dilemma between effectively controlling carbon emissions and energetically promoting economic development. To deal with climate change, it is a top priority

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for all the developing countries, including China and other countries, to formulate plans to reduce the carbon emission effectively with the goal of economic growth and social welfare enhancement.

In formulating plans to reduce carbon emission, it could impose restrictions on carbon emission for all industries, or impose restrictions only for specific industries, especially for high energy-consuming industries (Horvath, 2000). High energy-consuming industries refer to industries in which energy consumption in the production process accounts for a relatively large proportion of the inputs, and are also called energy-intensive industries. For example, the National Bureau of Statistics of China defines high energy-consuming industries as six major industries, including the manufacturing industry of chemical materials and products, non-metallic mineral products industry, ferrous metal smelting and rolling processing industry, non-ferrous metal smelting and rolling processing industry, oil processing and coking & nuclear fuel processing, production and supply of electric power and hot power. As the major carbon emission industries, the carbon emission reduction effects of high energy-consuming industries determine the realization process of carbon emission reduction targets to a large extent.

There are two typical policies to reduce carbon emission. One is the carbon emission reduction constrains for all industries, and the other is for high energy-consuming industries. Under the emission reduction targets, the one which has minimal adverse impacts on social welfare and economic growth can adequately reflect the effectiveness of the carbon emission reduction. China is in the middle-late stage of industrialization, and factor-driven characteristics of relying heavily on resources and energy are obvious. The comparative analysis of the effects of carbon emission reduction constrains on all industries and on high energy-consuming industries in China can not only achieve the scientific evaluation of carbon emission reduction policies, but also provide references for the formulation of carbon emission reduction policies to many developing countries. More importantly, for developing countries and countries vulnerable to the adverse effects of climate change, the carbon reduction policy that can balance welfare enhancement and economic growth is an effective way to break the restrictions of resources and environment. So that, the countries could make contribution to the global efforts to combat climate change in line with their own social and economic sustainable development.

2. Literature review

2.1. The types of carbon emission reduction policies

The implementation of carbon reduction policy can be either targeted at the whole industry, or only for some key industries. In the study of overall emission reduction in all industries, scholars mainly consider two aspects which of the efficiency and fairness to make carbon reduction share allocation and path optimization design (Boyd et al., 2002; Marklund and Samakovlis, 2007; Morris et al., 2012; Raupach et al., 2014). Taking the decomposition of the overall emission reduction target between regions as an example, Zhang et al. (2013) pointed out that to achieve the same emission reduction target, it leads to lower emission reduction costs and less welfare losses using the principle that the marginal cost of emission reduction is the same in each region, compared with imposing the emission reduction restrictions on each region separately.

Compared with the carbon emission reduction in all industries, the effectiveness of carbon emission reduction for some key industries has been widely challenged. For instance, it may lead to CO_2 emissions transfer among the industries when carbon emission reduction constraints are imposed on some but not all industries, that is the phenomenon of carbon leakage (Felder and Rutherford, 1993; Pan et al., 2008). The reasons of inter-industry carbon transfer or carbon leakage are various, such as the difference of input structure in various industries and the relative price difference between industries (Peters and Hertwich, 2008; Paroussos et al., 2015; Guo et al., 2018). Many scholars consider that due to the carbon leakage, the effects of carbon emission reduction for a part but not all industries are greatly weakened.

There are many kinds of literature on the mitigation effects of different policies on climate change and their comparisons (Masud et al., 2014; Vera and Sauma, 2015; Wang and Chen, 2015). However, the comparative analysis of carbon emission reduction on different targets, such as all industries and sectional industries, is rare. In this paper, we respectively specify carbon emission reduction policies for all sectors and partial sectors. Specifically, on the one hand, we set the overall carbon emission reduction target and use market mechanism that the marginal cost of emission reduction is the same among various industries, to achieve the effective emission reduction for all industries, which is called the carbon emission reduction in all industries. On the other hand, we select the high energy consuming industries as carbon emission reduction industries and simulate the effects of carbon emission reduction in key industries.

2.2. The effects of carbon emission reduction

In the research on the effects of carbon emission reduction policies, the influence of carbon emission reduction on economic growth is abundant (Liu et al., 2015; Fan et al., 2016). Tol (2009), Hassler and Krusell (2012) find that the economic growth in different regions has very different responses to carbon emission reduction policies. Among them, carbon emission reduction policies have significant negative impacts on economic output in some regions. However, for different examples, carbon emission reduction policies may optimize resource allocation and promote economic growth (Fischer, 2003; Fischer and Springborn, 2011). In addition to the influence for economic growth, there are many studies on the impacts of carbon emission reduction on economic structure, energy structure, and so on (Minihan and Wu, 2012; Fischer and Fox, 2012; Chiu et al., 2015). Some scholars have studied the spillover effects of carbon transfer on economic growth and the optimal production level under carbon emission reduction targets (Sun et al., 2016; Cao et al., 2017).

However, the analysis of the impacts of carbon emission reduction on social welfare is relatively inadequate. Leach (2009) and Pindyck (2012) discuss the different impacts of various carbon emission reduction policies on economic growth, climate change and social welfare. They find that to achieve carbon emission reduction targets leads to social welfare costs increased. Some of the existing literatures also analyze the impacts of welfare factors on the policy effects of carbon emission reduction and the behavior of emission reduction agents. For instance, Ji et al. (2017) consider the impacts of low carbon preferences of consumers on carbon emissions from producers. The results show that the cap-and-trade mechanism is acceptable for supply chain members when consumers have a strong low-carbon preference. Xia et al. (2018) take social preferences and consumers' low-carbon awareness into consideration in the cap-and-trade system and analyses their influences on emission reduction motivation, profits and utilities of manufacturers and retailers.

Social welfare enhancement is a crucial goal in tackling climate change. Therefore, it is necessary to study the economic effects and welfare effects of carbon emission reduction. In this paper, to make scientific and reasonable judgments on the effectiveness of different carbon emission reduction policies, we attempt to compare the economic effects and welfare effects of emissions

reduction constrains for all industries and energy-intensive industries under the same carbon emission reduction target.

2.3. The innovation of this manuscript

In this paper, we try to evaluate and optimize the research of carbon emission reduction policies from four aspects:

(1) Since there is a two-way relationship between economic growth and carbon emissions, it may lead to endogenous problems using the simple regression model to analyze the relationship between them (Coondoo and Dinda, 2002). A dynamic general equilibrium model with carbon emission constraints could solve this problem effectively.
(2) The relationship between economy and carbon emission is mainly reflected in the flow of products and energy. The input-output model that describes product flows is an effective tool for environmental policy analysis (Leeuwen et al., 2016). Some scholars have used multi-sector or multi-regional input-output model to measure carbon emissions between industries or regions (Liu et al., 2016; Ward et al., 2017; Pan et al., 2018). This study introduces the input-output structure in a dynamic general equilibrium model and specifies a multi-industry dynamic general equilibrium model to fully demonstrate industry heterogeneity. It provides a new framework for the explanation of policy effects.
(3) Based on the perspective of inter-industry linkage, we describe the path and transmission mechanism of different carbon emission reduction policies on the economy and social welfare, which reflects the heterogeneity of industrial emission reduction effects. In other words, after setting carbon emission reduction constraints into the dynamic general equilibrium model, we could evaluate the policy effects of carbon emission reduction under the dual objectives of economic growth and welfare improvement, and enrich the research system of carbon emission reduction policy effects.
(4) DSGE (Dynamic Stochastic General Equilibrium) can avoid Lucas Critique and well study the dynamic impacts of different types of random shocks on various variables in the economic system, while DGE (Dynamic General Equilibrium) is mainly used to study the impacts of deterministic changes of external constraints or adjustments of policy objectives on variables in the economy. Therefore, DSGE model is more suitable for studying random impacts, and DGE model has a comparative advantage in analyzing deterministic shocks. DGE model can be used to apply specific and deterministic carbon emission reduction constraints to key industries. By using DGE model, we can take full advantage of the general equilibrium model embedded in the input-output structure.

The rest of the paper is organized as follows. Section 3 is the research design, by the basis of the formulation and implementation process of China's carbon emission reduction policy, we establish a multi-industry dynamic general equilibrium model, and perform parameter calibration and model solving. Based on this model, Section 4 conducts the comparative analysis of the welfare effects of carbon emission reduction in all industries and in high energy-consuming industries under the same carbon emission reduction target. In Section 5, from the perspective of economic effects, we analyze the impacts of carbon emission reductions in all industries and in high energy-consuming industries on output levels and employment levels. The last part is the conclusion.

3. Research design

3.1. Policy making and implementing process of carbon emission reduction in China

According to economic development and emission reduction potential in international policy system and policy targets, different country adopts different emission reduction policies, i.e. reduction policy of total carbon emission and reduction policy of carbon intensity. Specifically, a total reduction of carbon emission is the absolute reduction scheme while intensity reduction is the carbon emission reduction per unit of GDP, which is a relative reduction program. Developed countries tend to adopt a total reduction policy of carbon emission while developing countries prefer intensity reduction policy of carbon emission. Because these countries take many factors into consideration, such as industrialization promoting, domestic economy development and social welfare improvement, to balance the relationship between economy development and carbon emission reduction. Like most developing countries, China is also implementing an intensity reduction policy of carbon emission.

In June 2007, China released its first national climate change program, which influenced the formulation of relevant regulation of climate change and emission reduction targets significantly. Since then, China has identified the year 2020 and 2030 as two critical time points for carbon emission reduction. To be specific, in 2009, the Chinese government announced that CO_2 emissions per unit of GDP would fall by 40%~45% by 2020. In 2015, China pointed out in the national autonomous contribution targets that carbon emission would reach the peak and China would strive to reach as soon as possible, CO_2 emission per unit of GDP would decline by 60%~65% from 2005 to around 2030.

The administrative command is the main way for China's central and local governments to push forward carbon emission reduction. More specifically, the superior government usually breaks down the responsibility based on the overall national overall target of carbon emission reduction, then assign part of it to the inferior government. But in the process of current carbon emission reduction, there are many shortcomings in the traditional command and control model. For example, sources of information and scientific evaluation methods are not sufficient; emission allowance is hard to achieve reasonable distribution in different provinces and regions. If unified standards have been used, flexibility lacks and low efficiency would be caused inevitably in the process of emission reduction. Hence, the effects of reduction policy of traditional administrative carbon reduction would be limited.

How to make the full use of market-oriented environmental management instruments, make market mechanism to play a dominant role in resource allocation and price guidance, and minimize the cost of completing the reduction target of carbon emission are key factors to implement reduction policy of carbon emission. In the market mechanism of carbon emission reduction, China mainly participates in or implements carbon trading emission reduction and carbon trading can be divided into international and domestic project-based and quota-based categories. Concerning international carbon trading, Clean Development Mechanism (CDM), which China participates in early, is a project-based trading market. That is, developed countries implement reduction projects of greenhouse gas emission in developing countries to obtain project-level emission reduction offset. For the time being, China is the largest supplier of global Clean Development Mechanism projects.

In terms of domestic carbon trading, in 2011, China selected seven provinces and cities as carbon trading pilots, including Beijing, Tianjin, Shenzhen, Hubei and so on. In 2013, carbon trading

was launched officially, and the trading varieties of pilot provinces and cities mainly include carbon emission allowance, certified emission reduction etc. On this basis, in order to build a unified carbon trading market, the Chinese government initiated the national carbon emission trading system in December 2017. The target of carbon trading is the overall control of total carbon emission, while some pilot regions choose carbon intensity targets. Because different choice might lead to different market trading, scientific evaluation and comparative analysis of effects of different target options are needed for further research.

3.2. Model specification

Based on the research of Dissou and Karnizova (2016) and Caron (2012), according to the differences in their production activities and carbon emissions, this paper combines 42 industries of China's Input-Output Table (2012) into 8 industries, including agriculture, coal industry, oil & gas industry, high energy-consuming industry, low energy-consuming industry, construction industry, producer service industry and consumer service industry And then, we specify a multi-industry dynamics general equilibrium model including a representative household, a government and 8 production sectors. In the general equilibrium framework with input-output structure, it is possible to analyze the transmission effects among different industries of carbon emission reduction in all industry and in high energy-consuming industries.

3.2.1. Representative household

Referring to Barrage's study (2016) and considering the impacts of carbon emission and the resulting climate change on people's living environment as well as their lifestyle, we introduce negative externalities of carbon emissions in the utility function of the representative household in this paper. The utility function includes consumption, leisure time and carbon emissions factors:

$$U_t(C_t, L_t, X_t) = \ln C_t + \chi \ln(1 - L_t) - \nu(X_t) \tag{1}$$

where C_t is the total consumption level in t-th period. L_t is the total hours of labor or total labor inputs. Therefore, $1-L_t$ stands for leisure time. X_t represents the carbon stock formed by carbon accumulation and $\nu(\cdot)$is influence function of carbon stock on the utility of the representative household. χ is the substitution parameter of consumption and leisure time.

The representative household aims to maximize the life-long utility, and the objective function is shown in equation (2).

$$E_0 \sum_{t=0}^{\infty} \eta^t U_t(C_t, L_t, X_t) = E_0 \sum_{t=0}^{\infty} \eta^t [\ln C_t + \chi \ln(1 - L_t) - \nu(X_t)] \tag{2}$$

where η is the discount rate.

The representative household provides capital and labor factors to obtain income, and then use the income for consumption and investment. Therefore, the budget constraints can be expressed as:

$$P_t C_t + Q_t I_t \le w_t L_t + r_t K_t + \prod_t \tag{3}$$

where the price of the total consumption C_t is P_t. I_t and Q_t are the total investment and its price respectively. w_t is the wage of labor L_t. r_t is the rent of total capital K_t. Π_t is the total profit of all production sectors in the economy. The relationship between investment and capital accumulation could be reflected by the dynamic accumulation equation of capital $K_{t+1} = (1-\delta)K_t + I_t$, in which $\delta$is the depreciation rate.

As mentioned above, there are 8 production sectors in the economy, such as agriculture, the coal industry, high energy-consuming industries, and so on. We specify the identity of the production sector as h, $h = 1, 2, \ldots, N$, $N = 8$. In general, it could be assumed that capital and labor in the economy are homogeneous. Therefore, the capital K_t^h and labor L_t^h of each production sector can be added to obtain the total capital K_t and the total labor input L_t directly. That is $K_{t=}\Sigma_h K_t^h$, $L_{t=}\Sigma_h L_t^h$.

However, due to the large differences of products among industries, when the products of each sector is used as the final demand, the product C_t^h for consumption and the product I_t^h for investment can't be added together directly. They should be combined into total consumer goods C_t and total investment products I_t through functions. In this paper, we assume that the consumer goods C_t^h and investment products I_t^h in each sector could be added respectively by using the Cobb-Douglas functions. Taking investment products as an example, the formula is shown in equation (4).

$$I_t = \prod_{h=1}^{N} \left(I_t^h\right)^{\xi_h} = \left(I_t^1\right)^{\xi_1} \left(I_t^2\right)^{\xi_2} \cdots \left(I_t^N\right)^{\xi_N},\ \mathrm{h} = 1,\ 2,\ \ldots,\ \mathrm{N},\ \mathrm{N} = 8 \tag{4}$$

where I_t^h is the investment product purchased by the representative household in the t-th period from the h-th production sector, and ξ_h is the substitution elasticity of investment products among different sectors.

Based on equation (4), we can obtain equation (5) to describe the relation between the price Q_t of total investment and the price P_t^h of the investment product of each sector.

$$Q_t = \prod_{h=1}^{N} \left(\frac{P_t^h}{\xi_h}\right)^{\xi_h} = \left(\frac{P_t^1}{\xi_1}\right)^{\xi_1} \left(\frac{P_t^2}{\xi_2}\right)^{\xi_2} \cdots \left(\frac{P_t^N}{\xi_N}\right)^{\xi_N} \tag{5}$$

where P_t^h is the price of the investment product of the h-th sector.

Similarly, total consumption C_t is also composed of consumer goods C_t^h of each sector via the parameter vector ζ_h. The price P_t of total consumer goods and price P_t^h of the consumer goods of each sector also fit in with the relationship similar to equation (5).

3.2.2. Production sectors

Corresponding to the structure of the input-output table, we set the production functions of the eight production sectors, such as agriculture, coal industry, high energy-consuming industries, and so on. The production sectors need to purchase non-energy intermediate products and energy intermediate products, lease capital and labor. Carbon emissions and carbon accumulation might have impacts on their production activities, especially on the grain production in agriculture. Therefore, referring to the model of Heutel (2012), this paper introduces the negative externalities of carbon emission accumulation into the production function and sets the production function of each sector as:

$$\begin{aligned} Y_t^h =& [1 - D(X_t)] A_t^h \left(K_t^h\right)^{\alpha_h} \left(L_t^h\right)^{\beta_h} \left(M_t^h\right)^{\gamma_h} \left(E_t^h\right)^{1-\alpha_h-\beta_h-\gamma_h}, \\ & \mathrm{h} = 1,\ 2,\ \ldots,\ \mathrm{N},\ \mathrm{N} = 8 \end{aligned} \tag{6}$$

where Y_t^h is the output of the h-th production sector in the t-th period. X_t represents the amount of carbon. $D(\cdot)$ is the influence function of carbon emissions on the production sector, also known as the loss of productivity. A_t^h is the technical level. K_t^h and L_t^h are the capital and labor used by the h-th sector respectively. M_t^h and E_t^h are respectively the non-energy intermediate products and energy intermediate products invested in the production process of the h-th sector. α_h, β_h and γ_h are the elasticity coefficients.

Each production sector maximizes its profits by optimizing a selection of non-energy intermediate products, energy intermediate products, labor and capital. The equation for maximizing profit in the h-th production sector is:

$$\prod_t^h = P_t^h Y_t^h - r_t K_t^h - w_t L_t^h - T_t^h M_t^h - J_t^h E_t^h \tag{7}$$

where T_t^h and J_t^h separately represent the prices of non-energy intermediate products and energy intermediate products in the h-th production sector. The profit of each production sector Π_t^h can be added together to get the total profit of all production sectorsΠ_t in the economy.

On the basis of equation (7), we can calculate the added value VA_t^h of the h-th production sector in the t-th period, which is shown in equation (8).

$$VA_t^h = P_t^h Y_t^h - T_t^h M_t^h - J_t^h E_t^h \tag{8}$$

By calculating the added value VA_t^h of all production sectors, we could get the total added value VA_t in the economy. It should be noted that when the production sectors pursue the profit maximization goal, the economic profits Π_t^h and Π_t are zero, while the added values VA_t^h and VA_t^h are not zero.

Similar to the products used for final demand, when the products of various sectors are used for intermediate needs, they cannot be added directly to obtain the total non-energy intermediate products M_t^h and energy intermediate products E_t^h. They should be combined through functions. Taking the non-energy intermediate products M_t^h invested by the h-th production sector in the t-th period as an example, the combination equation is:

$$M_t^h = \prod_{s=1}^{N'} \left(m_{s,t}^h\right)^{\chi_{sh}} = \left(m_{1,t}^h\right)^{\chi_{1h}} \left(m_{2,t}^h\right)^{\chi_{2h}} \cdots \left(m_{N',t}^h\right)^{\chi_{N'h}}, \quad \mathrm{s} = 1,\ 2,\ \ldots,\ \mathrm{N}',\ \mathrm{N}' = 6 \tag{9}$$

where s is the identity of the production sector of non-energy product, and N' is the number of non-energy production sectors. In this paper, except for the coal industry, oil and gas industry, the other six sectors are non-energy production sectors. $m_{s,t}^h$ represents the quantity of the non-energy intermediate products purchased from the s-th sector by the h-th sector. χ_{sh} is the substitution elasticity among the products $m_{s,t}^h$.

On the basis of equation (9), we could get the price T_t^h of the non-energy intermediate products M_t^h:

$$T_t^h = \prod_{s=1}^{N'} \left(\frac{P_t^s}{\chi_{sh}}\right)^{\chi_{sh}} = \left(\frac{P_t^1}{\chi_{1h}}\right)^{\chi_{1h}} \left(\frac{P_t^2}{\chi_{2h}}\right)^{\chi_{2h}} \cdots \left(\frac{P_t^{N'}}{\chi_{N'h}}\right)^{\chi_{N'h}} \tag{10}$$

where P_t^s is the price of non-energy intermediate products of s-th sector.

As the combination method of non-energy intermediate products, the energy intermediate products E_t^h of the h-th sector can be composed of coal products, oil and natural gas products. The expression of E_t^h's price J_t^h is similar to equation (10).

3.2.3. Carbon emission reduction constraints

In general, we assume that primary energy products such as coal, oil & natural gas generate carbon emissions. The carbon emission coefficients of coal, oil & natural gas are θ_1 and θ_2 respectively. It is easy to calculate the carbon emissions EM_t^h of the h-th production sector in the t-th period and the formula is shown as equation (11).

$$EM_t^h \sum_{j=1}^{N''} e_{j,t}^h \theta_j = e_{1,t}^h \theta_1 + e_{2,t}^h \theta_2,\ \mathrm{j} = 1,\ \ldots,\ \mathrm{N}'',\ \mathrm{N}'' = 2 \tag{11}$$

where j is the identity of the energy sector, and N'' is the number of energy sectors. $e_{j,t}^h$ represents the quantity of the energy intermediate products purchased from the j-th sector by the h-th sector. In this paper, the energy sectors include two major categories. One is coal sector, and the other is oil & natural gas sector.

Adding up the total carbon emissions EM_t^h of all production sectors, we can get the total carbon emissions in the economy EM_t, that is:

$$EM_t \sum_{h=1}^{N} EM_t^h,\ \mathrm{h} = 1,\ 2,\ \ldots,\ \mathrm{N},\ \mathrm{N} = 8 \tag{12}$$

For carbon emissions in the atmosphere, the ecosystem has a certain degree of degradation ability. The undegraded carbon emissions gradually accumulate to form carbon stocks, which would trigger the climate change. The formation process of the carbon stock is shown in equation (13).

$$X_t = (1-\rho)X_{t-1} + EM_t \tag{13}$$

where ρ is the intertemporal self-degradation coefficient of the ecosystem. The larger the coefficient, the stronger the ability of the ecosystem to degrade carbon emissions, and the less accumulated carbon emissions. The accumulated carbon emissions have certain impacts on people's living environment and enterprises' production activities. In this paper, we introduce carbon emission factors into the utility function of the representative household and the production function of production sectors, reflecting the impacts of carbon emissions on social welfare and economic output.

According to the definition of carbon intensity, based on equations (11) and (8), the carbon intensity INT_t^h of the h-th production sector in the t-th period is calculated as:

$$INT_t^h = EM_t^h \Big/ VA_t^h \tag{14}$$

Similar to equation (14), the overall carbon intensity INT_t in the economy is calculated as:

$$INT_t = EM_t \Big/ VA_t = \sum_{h=1}^{N} EM_t^h \Big/ \sum_{h=1}^{N} VA_t^h \tag{15}$$

Assuming that the government plans to reduce the overall carbon intensity to INT_0, we could obtain the overall constraint of carbon emission reduction:

$$INT_t \le INT_0 \tag{16}$$

Applying constraint (16) to all industries, according to the "cost effectiveness" principle that the shadow prices of carbon emission reduction in every industry are same, we can rewrite the constraint function of the carbon reduction program for all industries as equation (17):

$$\lambda_t (INT_t - INT_0) = 0 \tag{17}$$

where λ_t is the shadow price of carbon emission reduction in various industries.

Different from equation (16), the carbon emission reduction constraint can be applied to a specific industry, namely $INT_t^h \le INT_0^h$. At this time, the reduction constraint of carbon intensity can be set as:

$$\lambda_t^h \left(INT_t^h - INT_0^h \right) = 0 \quad (18)$$

where λ_t^h is the shadow price under carbon emission reduction in the h-th industry, and INT_0^h is the target of carbon intensity in the h-th industry. By converting and setting INT_0^h, the overall carbon intensity target INT_0 can be achieved. It should be noted that the high energy-consuming industry is the main energy consumption and carbon emission sector. To compare with the carbon emission reduction in all industries, we select the high energy-consuming industry to exert carbon emission reduction. In other words, we merely apply carbon emission constraint function (18) to high energy-consuming industries.

Therefore, equation (17) and equation (18) are the constraint forms of carbon reduction in all industries and high energy-consuming industries respectively. We add the two equations above respectively into the objective function of the profit maximization of the production sectors and calculate the model solution. Then we can obtain the effects of carbon reduction for all industries and high energy-consuming industries on the entire economy. It should be noted that the market clearing condition $Y_t^h = C_t^h + I_t^h + M_t^h + E_t^h$ ($h = 1$–8) and the price benchmark must be specified. For example, we can set the price of products in the first production sector as 1, namely $P_t^1 = 1$ to achieve the closure of the model.

3.3. Main parameters calibration

In this paper, we mainly calibrate the parameters based on the China Input-Output Table (2012) published by the National Bureau of Statistics of China. Before specifying the theoretical model, we have combined the industries into eight production sectors such as agriculture, coal industry, high energy-consuming industries and so on. After the combination of production sectors, the corresponding added value and final demand of each industry in the original input-output table are also incorporated into the new production sector. The new input-output table obtained can be used to calibrate the parameters in the model. Among them, according to the data of the intermediate input and the intermediate use of the first quadrant in the basic flow sheet of the input-output table, we can calculate the input coefficient matrix of the non-energy intermediate products. The elements in the matrix are χ_{sh}, as shown in Table 1.

Based on the final use part of the input-output table, we can calculate the elasticity coefficients or share coefficients of the products in each production sector when they are used for investment and consumption, as shown in Table 2.

According to the data of intermediate input and added value of production sectors in the input-output table, we calculate the proportion of non-energy intermediate products, energy intermediate products, capital and labor factors in the total output of each production sector, namely the coefficient of elasticity in production functions, listed in Table 3.

In addition, with reference to the parameters of Goulder and Schneider (1999), Pizer (2002) and Acemoglu et al. (2011), we specify the discount factor of the utility of representative household, the substitution parameter of consumption and leisure, the depreciation rate of capital and technical parameters of various production sectors. Referring to the model of Heutel (2012) and Barrage (2016), we specify the function form of the influences of carbon emission on the representative household and production sector. In addition, we calculate the carbon emission coefficients of coal, oil & natural gas according to the carbon emission coefficients and the calculation formula of carbon emission (the 2006 edition) issued by the Intergovernmental Panel on Climate Change (IPCC) to complete the calibration of main parameters.

3.4. Model solution

We use Matlab R2009a software to perform the program design and calculate model solution. According to the China's Input-Output Table (2012) and the calibration results, the carbon emissions of high energy-consuming industries accounted for 85.606% of all industries, so a decrease by 1% in the total emissions is equivalent to a 1.168% reduction in the emissions of high energy-consuming industries when the emissions of other industries are unchanged. Fig. 1 shows the overall carbon intensity changes in the economy under the two constrains of carbon emission reduction.

The core goals of reducing carbon emissions and tackling climate change are to improve social welfare and promote economic growth. When the carbon reduction effects of the two programs are made equivalent, the welfare effects and economic effects of them can be measured and compared under the same carbon emission reduction goal. Fig. 2 shows that in terms of welfare effects, we focus on the utility variable U of the representative household, the consumption variable C and C^h that are closely related to the utility. In terms of economic effects, the impacts of carbon reduction on economic output and employment are mainly analyzed, including the output variable Y and Y^h, the labor variable $L$and L^h.

4. Simulation analysis on the welfare effects of carbon reduction constrains

4.1. The changes of social welfare under different carbon reduction constrains

As shown in Fig. 3, when the overall carbon intensity in the economy is set to decrease by 1%–20%, the diagrams of social welfare changes under the constrains for all industries and high

Table 1
Input coefficient matrix of the non-energy intermediate products.

Parameter matrix (χ_{sh})	Agriculture	Coal industry	Oil &Gas industry	High energy-consuming industry	Low energy-consuming industry	Construction industry	Producer service industry	Consumer service industry
Agriculture	0.333	0.002	0.000	0.018	0.105	0.011	0.010	0.040
High energy-consuming industry	0.269	0.333	0.373	0.643	0.241	0.575	0.140	0.168
Low energy-consuming industry	0.278	0.291	0.466	0.200	0.502	0.181	0.252	0.264
Construction industry	0.000	0.007	0.004	0.002	0.002	0.037	0.018	0.014
Producer service industry	0.076	0.291	0.118	0.099	0.088	0.154	0.461	0.346
Consumer service industry	0.045	0.076	0.039	0.038	0.062	0.042	0.118	0.168

Table 2
The share parameters of the products used for final demand.

Share parameters	Agriculture	Coal industry	Oil &Gas industry	High energy-consuming industry	Low energy-consuming industry	Construction industry	Producer service industry	Consumer service industry
Parameters of investment (ξ_h)	0.027	0.001	0.001	0.003	0.343	0.519	0.083	0.022
Parameters of consumption (ζ_h)	0.078	0.001	0.000	0.043	0.255	0.000	0.201	0.423

Table 3
The parameters of elasticity of intermediate products and factors in outputs.

Elastic parameters	Agriculture	Coal industry	Oil &Gas industry	High energy-consuming industry	Low energy-consuming industry	Construction industry	Producer service industry	Consumer service industry
Capital (α_h)	0.093	0.242	0.488	0.139	0.125	0.104	0.329	0.248
Labor (β_h)	0.492	0.251	0.123	0.065	0.093	0.161	0.161	0.342
Non-energy Intermediate products (γ_h)	0.414	0.347	0.378	0.678	0.777	0.734	0.508	0.407
Energy Intermediate products ($1-\alpha_h-\beta_h-\gamma_h$)	0.001	0.160	0.011	0.118	0.006	0.001	0.001	0.002

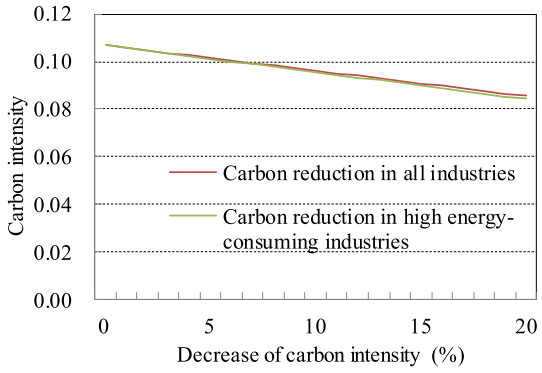

Fig. 1. Equivalent carbon emission reduction effects under two different constrains

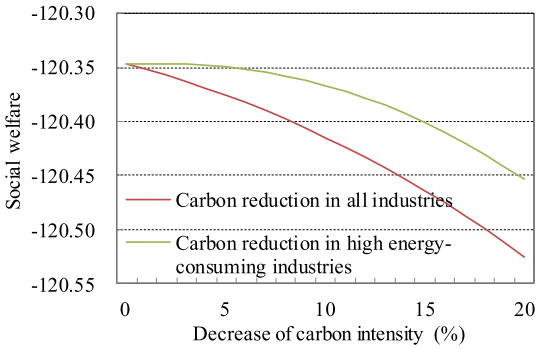

Fig. 3. The changes of social welfare under different carbon reduction constrains

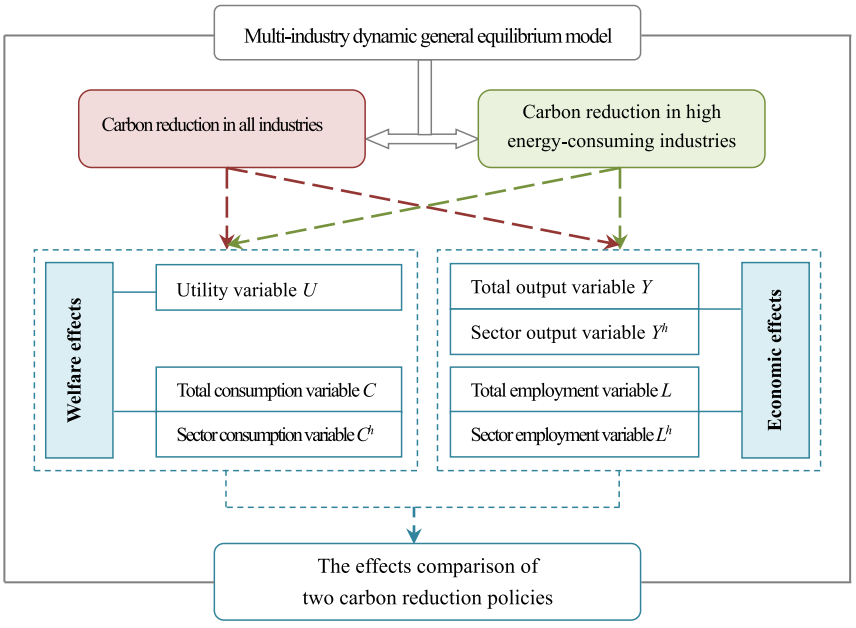
Multi-industry dynamic general equilibrium model
Carbon reduction in all industries
Carbon reduction in high energy-consuming industries
Welfare effects
Utility variable U
Total consumption variable C
Sector consumption variable C^h
Total output variable Y
Sector output variable Y^h
Total employment variable L
Sector employment variable L^h
Economic effects
The effects comparison of two carbon reduction policies

Fig. 2. Object variables for the comparative study of carbon reduction policies.

energy-consuming industries are obtained through simulation.

When carbon reduction policy is carried out, the social welfare demonstrates a clear downward trend. Actually, carbon reduction restriction has both positive and negative effects on social welfare. On the one hand, it may restrict enterprises' economic production activities, reduce household consumption to a certain extent and thus causing a negative impact; On the other hand, it slows down the speed of carbon emissions to some extent and plays a positive role in improving the ecological environment, thereby enhancing social welfare. The two effects determine the changes in social welfare together. Apparently, the negative effects of carbon reduction on social welfare are larger than the positive effects, resulting in the decrease of social welfare.

Comparing the curves of social welfare changes under the two carbon emission restrictions, it could be seen that the decline in social welfare is faster and greater under the restriction for all industries, in which the carbon reduction objective is shared among various industries, forming joint reduction effects among production sectors. All industries are subject to carbon emission restriction, leading to broader and deeper impacts on economic output, income, consumption, social welfare and so on. Compared with carbon emission restrictions for all industries, constrains for high energy-consuming industries are significantly smaller in terms of influence degree. For instance, the impacts of carbon emission constrain for high energy-consuming are transmitted to certain related industries only through intermediate input-output relationships. As a result, the economic outputs of various sectors and the income of representative households indicate a smaller decline. For consumption, products of high energy-consuming industries take up a very low proportion in household goods; therefore, the carbon reduction in high energy-consuming industries has little impact on the utility of the household and social welfare.

4.2. The changes in consumption levels under different carbon reduction constrains

Consumption is an important manifestation of household utility and social welfare. The curve of total consumption in the economy is given in Fig. 4 when the overall carbon intensity decreases by 1%–20%. Comparing Figs. 3 and 4, with the enhancement of the constraints, the total consumption level shows a significant downward trend, which is similar to the social welfare variable. The decline is greater under the constraints of carbon reduction in all industries, which is also consistent with the characteristics of changes in social welfare.

To further reflect the differential impacts of carbon reduction constrains on the consumption of different products, the consumption changes of various sectors' products are calculated under carbon reduction constrains, as shown in Table 4, in case of 5%, 10%, 15%, and 20% decreases in overall carbon intensity in the economy.

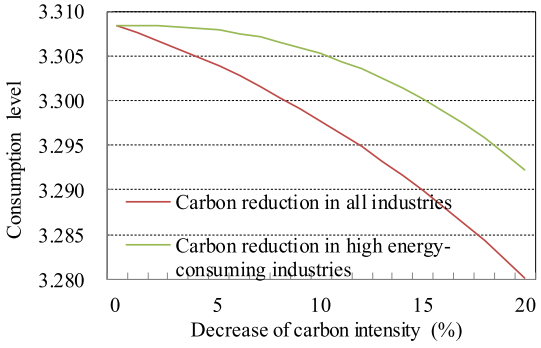

Fig. 4. The changes of consumption under different carbon reduction constrains

Table 4 reflects that there are large differences in the consumption changes of various sectors' products under the carbon emission reduction in all industries. For example, when the overall carbon intensity decreases by 5%, changes in the consumptions of high energy-consuming industrial products and coal products are −1.048% and −0.827% respectively, with declining rates significantly higher than those of low energy-consuming products and producer services. On the contrary, the consumptions of consumer services and agricultural products show a rising trend. When carbon reduction in all industries is carried out, the social costs of carbon emission are added by various industries into their private costs. The rises in production costs lead to increases in product prices and change in the relative price system. As an important signal of resource allocation in the market, the income effects and substitution effects caused by relative price changes in various industries are the main causes for the changes in the consumptions.

Since the marginal abatement costs of various industries are assumed equal under the carbon emission reduction in all industries, the difficulties and costs are higher for high energy-consuming industries and coal industry in reducing carbon emissions. For agriculture and consumer service industries, it is easy for them to adjust the intermediate input structure. That is, they can use more capital, labors and other factors to replace intermediate products, so as to achieve the carbon reduction targets while keeping product prices relatively stable. More importantly, compared with other industries, their price elasticities of demand are relatively small, further reducing fluctuations in the consumption of their products.

Different from the carbon reduction in all industries, under the restrictions for high energy-consuming industries, except for the consumer service industry, declines in the products consumption of all other industries are smaller. That reflects the comparative advantage of carbon reduction in high energy-consuming industries in maintaining consumption stability. For example, except for the change of −0.803% in the consumption of high energy-consuming industrial products, the remaining 7 industries have experienced changes from −0.391% to −0.595% when the overall carbon intensity drops by 20%.

When carbon reduction is implemented in high energy-consuming industries, the most direct negative impact is on their own products, with the rising of the prices and decreasing of the demand. Then the effects of the increasing prices can be transmitted to other industries through the input-output relationships among industries, causing the production costs and product prices of other industries rise. Compared with the carbon reduction in all industries, the constraints in high energy-consuming industries have smaller and indirect effects on rising prices and decreasing demand in various industries. Moreover, an industrial linkage is a key element to influence the transmission effects of carbon reduction constraints in high energy-consuming industries. In addition to high energy-consuming industries themselves, the declines in consumptions are slightly higher about the construction industry, low energy-consuming industries and the oil & gas industry that are highly related to high energy-consuming industries.

Therefore, based on the perspective of welfare effects, under the carbon emission reduction in high energy-consuming industries, the social welfare level is higher than that under the reduction in all industries. In other words, carbon emission reduction in high energy-consuming industries could stabilize social welfare effectively.

Table 4
The changes in consumption of various sectors under carbon reduction constrains (%).

Carbon reduction policy	5%		10%		15%		20%	
	All industries	High energy-consuming industries	All industries	High energy-consuming industries	All industries	High energy-consuming industries	All industries	High energy-consuming industries
Agriculture	0.018	−0.010	0.005	−0.073	−0.041	−0.197	−0.124	−0.391
Coal industry	−0.827	−0.014	−1.730	−0.093	−2.715	−0.244	−3.791	−0.479
Oil & gas industry	−0.204	−0.018	−0.467	−0.107	−0.794	−0.278	−1.192	−0.545
High energy-consuming industry	−1.048	−0.031	−2.183	−0.164	−3.414	−0.414	−4.749	−0.803
Low energy-consuming industry	−0.316	−0.018	−0.688	−0.107	−1.123	−0.278	−1.628	−0.544
Construction industry	−0.449	−0.020	−0.960	−0.118	−1.540	−0.304	−2.195	−0.595
Producer service industry	−0.073	−0.015	−0.193	−0.097	−0.368	−0.254	−0.601	−0.498
Consumer service industry	0.003	−0.012	−0.032	−0.084	−0.109	−0.223	−0.234	−0.439

5. Simulation analysis of the economic effects of carbon reduction constrains

5.1. The changes of economic outputs under different carbon reduction constrains

Since energy consumption is the main source of carbon emissions, the carbon reduction policy can be considered essentially as a constraint on energy, restricting economic production activities through control of carbon emissions and energy input. As shown in Fig. 5, with the decrease of carbon intensity, the total economic outputs have shown characteristics of decline. Compared with the carbon reduction constrain for high energy-consuming industries, the carbon reduction in all industries is stricter with higher degree of restrictions on factor inputting and energy using. In addition, the effects of the latter are broader and it is more difficult for various industries to make sufficient adjustment to production structure through factor substitution, leading to a greater drop in total output.

Similar to Table 4, the declines in consumptions of various sectors' products are calculated, as shown in Table 5, under the two constrains of carbon emission reduction in case of 5%, 10%, 15%, and 20% decreases of the overall carbon intensity.

From Table 5, it can be seen that the outputs of various industries under carbon reduction constraints have shown a certain degree of decline, which is consistent with the change of total output in the economy. The negative impacts of carbon reduction on the production activities of various industries are mainly due to the reduction of intermediate inputs such as energy-intensive products and energy products. To achieve the target of carbon reduction, it is necessary to cut the input of primary energy products such as coal, oil& natural gas. Since each industry has reliance, directly or indirectly, on primary energy products, carbon reduction causes significant spillover effects through intermediate demand linkages between energy sector and other sectors. As a result, the outputs of various industries decrease due to reduced sources of input. Although various industries might stabilize their production scale by factor substitution, for example, increasing non-energy intermediate products, the impacts of the reduction of energy intermediates on production are dominating, eventually leading to declining outputs of various industries.

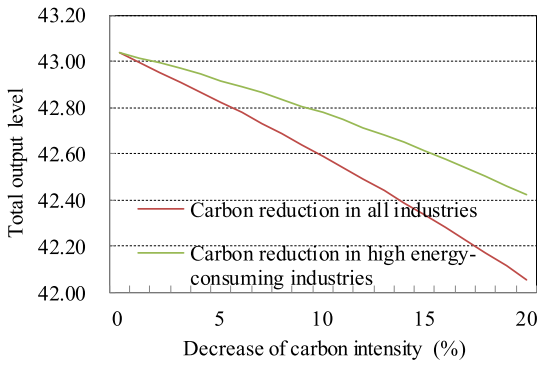

Fig. 5. The changes of total output under different carbon reduction constrains

Of all industries, the coal industry and the oil & gas industry suffer largest declines in their outputs. When the overall carbon intensity decreases by 20%, their outputs drop by more than 20%, well above those of agriculture, consumer service industry and other industries. As mentioned above, the consumption decreases of primary energy products such as coal, oil & gas by other industries exert negative effects on energy industries on the demand side. Meanwhile, the reduction in the supply of intermediate products from energy industries to other industries causes a rapid increase in the prices of energy products, thus further reducing the demand of energy products in various industries. As a result, there may be cyclical and cumulative cutbacks in the demand for products of energy industries, resulting in further declines in the outputs of the coal industry and the oil & gas industry.

However, there are some differences in the characteristics of outputs' decreases of the two energy industries under the different constrains of carbon reduction. As is shown in Table 5, the output of coal industry has declined more than that of oil & gas industry under carbon reduction in all industries. Conversely, under carbon reduction in high energy-consuming industries, the output of oil & gas industry suffers a bigger decline. That mainly due to the differences in the energy consumption structure between the overall economy and high energy-consuming industries. At present, China's energy consumption is still characterized by coal-based energy consumption structure. According to data released by the National Bureau of Statistics of China, China's coal consumption accounted for 60.4% of the total energy consumption in 2017. Therefore, the coal industry suffers the most loss under the carbon reduction in all industries. In contrast, high energy-consuming industries have consumed most of oil & gas resources, and oil and natural gas take a higher proportion than coal in their energy consumption structure. According to the China's Input-Output Table (2012), high energy-consuming industries consume 93.802% of

Table 5
The changes of outputs of various sectors under carbon reduction constrains (%).

Carbon reduction policy	5%		10%		15%		20%	
	All industries	High energy-consuming industries	All industries	High energy-consuming industries	All industries	High energy-consuming industries	All industries	High energy-consuming industries
Agriculture	−0.128	−0.114	−0.284	−0.261	−0.472	−0.445	−0.696	−0.674
Coal industry	−5.565	−4.949	−11.067	−9.952	−16.510	−15.011	−21.892	−20.126
Oil & gas industry	−5.121	−6.084	−10.263	−12.112	−15.423	−18.082	−20.597	−23.995
High energy-consuming industry	−1.366	−0.303	−2.808	−0.674	−4.335	−1.126	−5.954	−1.675
Low energy-consuming industry	−0.551	−0.204	−1.154	−0.450	−1.815	−0.747	−2.541	−1.104
Construction industry	−0.576	0.043	−1.210	0.073	−1.907	0.083	−2.674	0.065
Producer service industry	−0.274	−0.180	−0.592	−0.405	−0.962	−0.682	−1.387	−1.022
Consumer service industry	−0.080	−0.081	−0.198	−0.212	−0.357	−0.401	−0.563	−0.657

all oil & gas intermediate products. Besides, of the total intermediate input in high energy-consuming industries, oil & gas products account for 8.375%, almost 2% higher than coal products (6.385%). Therefore, compared with the coal industry, carbon reduction in high energy-consuming industries has a greater impact on the outputs of the oil & gas industry.

5.2. The changes of employment under different carbon reduction constrains

When the supply of intermediate products such as energy products decreases and their prices rise under the constraints of carbon reduction, the relative price of labor goes down, and on the whole, the total labor input in the economy increases. With a strengthening constraint, the growth of labor input becomes more prominent. According to Fig. 6, when the two policies of carbon emission reduction are implemented, both total labor inputs present notable increases. However, their growth characteristics are quite different. When the targets of carbon reduction are being set higher gradually, total labor input in the economy under the carbon reduction in all industries indicates a steady growth. While under the high energy-consuming industry, it goes up slowly at the beginning, followed by a rapid rise. This is a comprehensive result of the changes in labor input in various industries.

The diagrams of changes in labor in various industries under the carbon emission reduction constrains are given in Fig. 7. Under the carbon emission reduction in all industries, the labor inputs in various industries have shown a steady growth or varying degrees of increase, except for the coal industry and the oil & gas industry. As mentioned above, under the influence of the rising prices of energy intermediate products, clean intermediate products and labor may be used in various industries to replace energy products, leading to the increase of demand for labor in various industries. However, for the coal industry as well as the oil & gas industry, because of sharp decreases in product outputs under carbon reduction restrictions, the labor cutback caused by output decreases exceeds the labor growth arising from relative price changes. As a result, the demands for labor in the two energy industries decline.

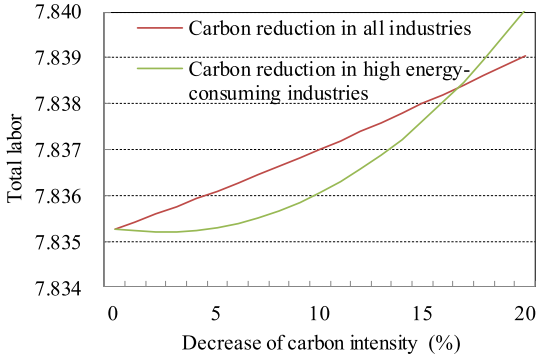

Fig. 6. The changes of total labor under different carbon reduction constrains

Significantly different from the characteristics of changes in the labor input under the constrains for all industries, as shown in Fig. 7, the labor inputs in various industries almost demonstrate a downward trend under the carbon reduction in high energy-consuming industries, except for high energy-consuming industries themselves and the construction industry. The reason is that when carbon reduction is implemented specifically for high energy-consuming industries, the major consequences are the decreased energy consumption and outputs in those industries, while the impacts on production activities are limited with regard to the industries using energy-intensive products as intermediate inputs. Due to the inertia of production patterns and production input structures, other industries are hammered passively by the negative impacts of carbon reduction in high energy-consuming industries on their production to a certain extent, which leads to the reduction of the scale of production and labor input accordingly.

For the high energy-consuming industries and the construction industry, they use a large number of energy-intensive products as intermediate inputs in their production processes. Based on the China's Input-Output Table (2012), it is calculated that of the total intermediate input in high energy-consuming industries, the intermediate supplies by themselves accounted for 54.778%.Similarly, the energy-intensive products take up a proportion of 57.466% in the total intermediate input of the construction industry. As the constraint of carbon reduction in high energy-consuming industries is tightened, the impacts of carbon reduction on the production of the construction industry are increasingly severe. The two kinds of industries have to change their input structures and re-allocate input factors, replacing energy-intensive products with more labor. Among them, the growth of labor in high energy-consuming industries is particularly significant.

From the perspective of economic effects, it could be concluded that compared with carbon reduction in all industries, the economic output level is higher but the employment level is slightly lower under the carbon emission reduction in high energy-consuming industries. In other words, the two programs of carbon emission reduction have their respective advantages in terms of economic effects.

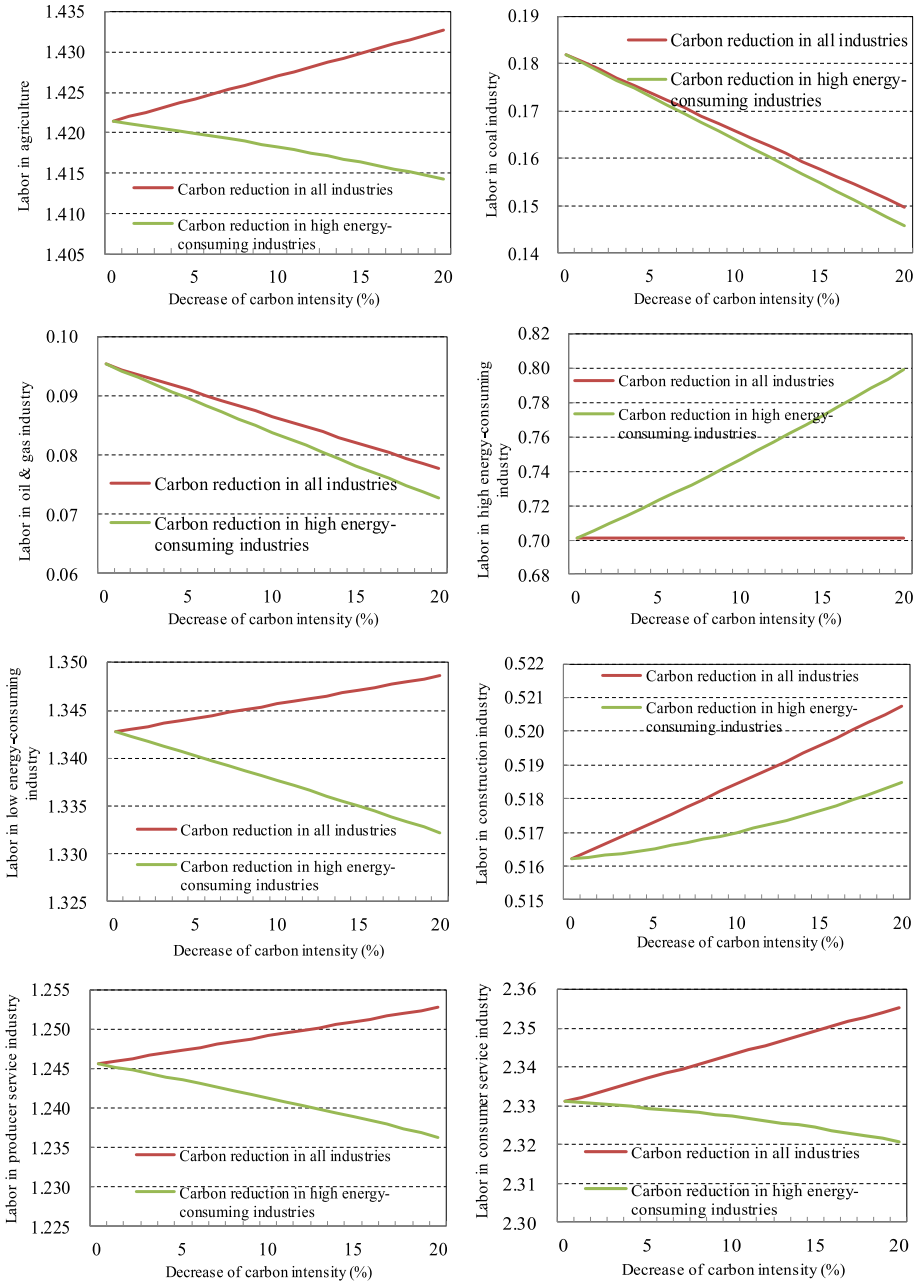
Labor in agriculture
Labor in coal industry
Labor in oil & gas industry
Labor in high energy-consuming industry
Labor in low energy-consuming industry
Labor in construction industry
Labor in producer service industry
Labor in consumer service industry
Carbon reduction in all industries
Carbon reduction in high energy-consuming industries
Decrease of carbon intensity (%)

Fig. 7. The changes of labor in various industries under different carbon reduction constrains

6. Conclusion

In this paper, a dynamic general equilibrium model with input-output structure was specified to compare the economic effects and welfare effects under the carbon emission reductions in all industries and high energy-consuming industries. The purpose is to obtain scientific judgment on the effectiveness of different carbon reduction policies. Main conclusions are as follows.

First, under the constraints of carbon reduction, social welfare shows a notable downward trend. Compared with the carbon reduction in high energy-consuming industries, social welfare decreases at a greater rate and in a larger extent with the carbon reduction in all industries. The reason is that under carbon reduction constrains for all industries, every industry is subject to restrictions while the scope of influence is remarkably smaller under the carbon reduction in high energy-consuming industries. With the tightening of carbon reduction restrictions, the changes in the total consumption and the consumption of products in various sectors are more significant under the carbon reduction in high energy-consuming industries. By contrast, carbon reduction in high energy-consuming industries shows relative advantages in maintaining the stability of social welfare and consumption level.

Second, with regard to the economic effect, compared with the carbon reduction in high energy-consuming industries, the carbon reduction in high energy-consuming industries imposes greater limitations on energy using, leading to larger decreases in the total output and outputs of various industries. Under the constraints of

carbon reduction, the changes of relative price have contributed to the growth of total labor input in the economy. There is a great difference in the characteristics of labor growth in various industries under different constrains of carbon emission reduction. When the carbon reduction in all industries is carried out, labor inputs of most industries have shown varying degrees of rising, except for the coal industry and the oil & gas industry. However, when carbon reduction is carried out specifically for high energy-consuming industries, most of the industries have shown a downward trend in labor input except for the high energy-consuming industries themselves and the construction industry. In terms of economic effect, the two programs of carbon emission reduction have respective advantages in maintaining output level or promoting employment.

Based on the research of this paper, we can conclude that in formulating carbon emission reduction programs, it is necessary to set constraints for some industries at the beginning and then gradually spread them to all industries. When carbon reduction is implemented for some key industries, such as high-carbon emission industries, attention should be paid to the changes of labor in various industries, preventing excessive employment growth in high energy-consuming industries. In the process of expanding carbon reduction, the impacts on energy consumption, economic output, social welfare and other aspects should be closely monitored. Developing and introducing clean energy production technologies need to be accelerated, so as to mitigate the impacts of carbon emission reduction on economic output and social welfare.

In the process of carbon emission reduction, China is currently implementing the method of task decomposition, which is determined by datum line method and historical emission method. However, to truly achieve effective emission reduction, it is necessary to achieve overall emission reduction targets by calculating and evaluating the impacts of marginal emission reduction costs and carbon emission reduction policies of various industries based on the characteristics of industry's own factor structure, under the principle of preventing excessive growth of output and employment in high energy-consuming industries. What's more, for influential and sensitive enterprises in high energy-consuming industries, open access is needed to participate in carbon trading in the process of building a unified carbon trading market in China. Thus, it can reduce the dependence of industries on high energy-consuming products and energy by key industries' influence on price transmission and intermediate input structure. When carbon emission reduction plan optimized, existing carbon emission reduction constraints of some industries in China should be gradually extended to all industries. When realizing the carbon emission reduction target, coordinated and sustainable development of economy and society should be promoted.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.01.183.

Appendix

According to the statistical classification standards issued by the China National Bureau of statistics, we classify the industries in China's Input-Output table in 2012 as:

Post-merger industries	Industries in China's Input-Output table
Agriculture	Agriculture, Forestry, Animal Husbandry, Fishery, Services in Support of Agriculture
Coal industry	Mining and Washing of Coal
Oil & natural gas industry	Extraction and Processing of Petroleum and Natural Gas
High energy-consuming industry	Processing of Petroleum, Coking, Processing of Nuclear Fuel
	Chemical Industry
	Manufacture of Nonmetallic Mineral Products
	Smelting and Rolling of Metals
	Production of Supply of Electric Power and Heat Power
Low energy-consuming industry	Other industries in the mining and manufacturing industries except the high energy consuming industries, the energy industries
Construction industry	Construction industry
Producer Service industry	Traffic, Transport, Storage and Post
	Information Transmission, Software and Computer Services
	Financial Intermediation
	Real Estate
	Leasing and Business Services
	Scientific Research and Experimental Development
Consumer Service industry	Wholesale and Retail Trades
	Hotels and Catering Services
	Management of Water conservancy, Environment and Public Facilities
	Services to Households, Repairs and Other Services
	Education
	Health and Social Work
	Culture, Sports and Entertainment
	Public Management, Social Security and Social Organization

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